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SYNTHETIC FLIGHT TRAINING REVISITED

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Illinois University

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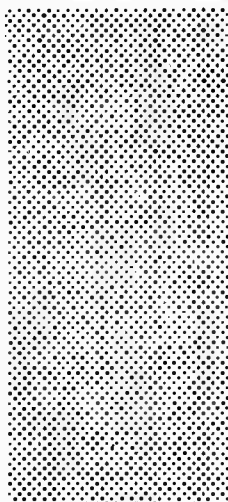
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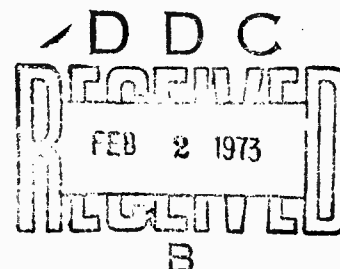
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## 13. ABSTRACT

Critical issues in the development and use of synthetic flight trainers are reviewed. Degree of simulation and fidelity of simulation are discussed as key design considerations. Problems of measurement of original learning, transfer, and retention are presented. Both transfer effectiveness and cost effectiveness are described as critical factors in the evaluation of flight trainers. Recent training innovations, such as automatically adaptive training, computer-assisted instruction, cross-adaptive measurement of residual attention, computer graphics, incremental transfer effectiveness measurement, and response surface methodology, are discussed as potential techniques for improving synthetic flight training. It was concluded that broader application of simulation is necessary to meet the new demands of pilot training, certification, and currency assurance in air transportation.

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Synthetic Flight Training Revisited

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Critical issues in the development and use of synthetic flight trainers are reviewed. Degree of simulation and fidelity of simulation are discussed as key design considerations. Problems of measurement of original learning, transfer, and retention are presented. Both transfer effectiveness and cost effectiveness are described as critical factors in the evaluation of flight trainers. Recent training innovations, such as automatically adaptive training, computer-assisted instruction, cross-adaptive measurement of residual attention, computer graphics, incremental transfer effectiveness measurement, and response surface methodology, are discussed as potential techniques for improving synthetic flight training. It was concluded that broader application of simulation is necessary to meet the new demands of pilot training, certification, and currency assurance in air transportation.

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PROLOGUE

It's only a paper moon  
Hanging over a cardboard sea,  
But it wouldn't be make believe  
If you'd believe in me.

It's only a canvas sky  
Sailing over a muslin tree,  
But it wouldn't be make believe  
If you'd believe in me.

Without your love,  
It's a honky tonk parade;  
Without your love,  
It's a melody played on a penny arcade.

It's a Barnum and Bailey world,  
Just as phony as it can be,  
But it wouldn't be make believe  
If you'd believe in me.

*Once popular ballad by Harold Arlen, Billy  
Rose, and Yip Harburg*

## BACKGROUND

Flight training at the close of World War I was a haphazard process at best. Basically, a new pilot was trained solely by demonstration and exhortation improvised by his particular flight instructor. The few flight-trainer type devices in use were short-winged aircraft, incapable of flight, known as "stub-winged Jennies" or "grass-cutters." Students would run these early trainers up and down a large field in an attempt to learn to control the craft.

Since those early days of flying, ground-based flight simulators and trainers have evolved from the famous Link "Blue Boxes" of World War II into precisely engineered devices capable of accurately computing the aerodynamic responses of an airplane to control inputs and of reproducing realistic cockpit instrument indications for all flight situations. But, despite the sophistication of contemporary simulators and the longevity of their use, many research issues concerning ground-based flight simulators and trainers remain unanswered. This paper is a review of trainer-related research with an emphasis on these unresolved questions.

### Why Simulate?

Obviously, the initial question is why use a simulator or trainer at all. According to Gagne (1962), the major difference between a simulator and the operational situation is that the simulator provides its users with greater control over ambient conditions. Whereas the real world is subject to unpredictable variations, a simulator provides planned variation of various elements of the real situation with unessential variables in the real situation omitted. The essential condition for effective training is that the simulator be procedurally faithful to the aircraft it is designed to represent. Determining which aspects of the operational situation can reasonably be left out is a central aspect of the simulator design process.

The second major advantage offered by simulators is that dangerous elements in the operational situation may be represented safely. For example, an aircraft simulator might represent an engine on fire by a flashing red light



rather than by an actual flame-producing fire. Furthermore, emergency procedures that would be too dangerous to teach in the air may be taught safely in ground-based devices.

A third advantage of simulators is their lower operating cost in comparison with the cost of operating counterpart aircraft. Simulator use is independent of weather or time of day, and the performance of individual flight tasks and procedures can be interrupted and repeated, thereby allowing errors to be corrected immediately and the distribution of practice on sequentially dependent flight tasks to be optimized. For these reasons, a major portion of any flight curriculum can be taught at a fraction of the cost of training in the equivalent aircraft.

#### How Can Simulation Be Used ?

Flight simulators and trainers have several uses. Initially, performance in a simulator or trainer can be used in pilot selection as a predictor of future success in training and operations. Second, a simulator that reproduces the aerodynamic responses of an aircraft with good fidelity is valuable for teaching new psychomotor skills required for operating an aircraft. Furthermore, the training functions of simulators are not limited solely to initial acquisition of flying skills. Trainers can be used effectively to familiarize an experienced pilot with the operating procedures and characteristics of an aircraft to which he is newly assigned. Such training should reduce the transitioning pilot's initial erroneous responses in the air resulting from negative transfer associated with the need to make different responses to highly similar stimuli. In addition, simulators can be used both to reassess and to maintain the proficiency of licensed pilots.

Proficiency assessment in a flight simulator is more economical and more readily controlled than a similar evaluation in the air. In fact, these devices have proven to be so useful that virtually all check rides for airline pilots are given in simulators rather than in their counterpart aircraft. Recently, commercial airline companies have conducted research to determine the feasibility of increasing the percentage of training in simulators for pilots of large jet aircraft. Results of studies conducted by both Trans World Airlines (1969) and American Airlines (1969)

indicate that experienced pilots can be trained to type-rating proficiency entirely in a flight simulator. In addition, performance evaluations in the simulator accurately predicted performance in the corresponding aircraft. These studies suggest that the Federal Aviation Administration could modify pilot certification requirements to allow increased use of simulation equipment of proven effectiveness.

### ISSUES IN FLIGHT SIMULATOR DESIGN

Smode, Hall, and Meyer (1966) have compiled a relatively comprehensive review of research studies using flight simulators and trainers for pilot training and have indicated areas in which additional research is needed. Although the terms simulator and trainer are sometimes used interchangeably, a distinction should be made: a simulator is designed to represent a specific counterpart vehicle or operational situation; a trainer is intended to represent a class of vehicles in various situations. Much of the research literature on simulation in pilot training can be subdivided into two areas: degree of simulation and fidelity of simulation. Degree of simulation refers to the inclusion of design features such as motion, extracockpit visual cues, and part-task versus whole-task representation. Fidelity of simulation refers to the accuracy with which design features represent or duplicate their real-world counterparts. The usual reason for striving for high fidelity of simulation is to maximize transfer of training to performance in the operational situation (Muckler, Nygaard, O'Kelly, and Williams, 1959). The following draws upon Smode's review of degree of simulation and Muckler's analysis of fidelity of simulation, supplemented by ideas of our own concerning issues in flight simulation research.

#### Degree of Simulation

Motion. Research findings dealing with motion simulation are as yet inconclusive. Results may be divided into three categories: those that support the value of motion, those that suggest that the value of motion depends upon the transfer task, and those that suggest that the value of motion is merely a transient effect.

Because motion provides the trainee with additional cues, many researchers have concluded that motion facilitates transfer performance (Besco, 1961; Buckhout, Sherman, Goldsmith, and Vitale, 1963; Ruocco, Vitale, and Binfari, 1965a; 1965b; Townsend, 1956). However, these studies evaluated learning with criterion trials in a simulator rather than in the air.

There has been some speculation that motion is strictly necessary only in specific situations, where acceleration cues either improve performance by facilitating anticipatory responses or hinder performance by making it more difficult for the pilot to make necessary control adjustments (Rathert, Creer, and Douvillier, 1959; Rathert, Creer, and Sadoff, 1961). A body of evidence suggests that although motion cues do seem to facilitate an initially higher level of performance, this effect rapidly fades with subsequent flight experience (Caro and Isley, 1966; Feddersen, 1961).

Several studies have linked the value of motion with the experience level of the pilot. Flexman (1966) and Briggs and Wiener (1959) noted that because experienced pilots often rely on motion rather than instrument readings, motion becomes more important as experience level increases. On the other hand, Muckler, Nygaard, O'Kelly, and Williams (1959) suggested that motion combined with contact cues is more important during the initial stages of learning. When visual and vestibular cues are conflicting, pilots tend to rely more upon their vestibular cues as their confidence in the visual information decreases (Johnson and Williams, 1971).

Smode, Hall, and Meyer (1966) indicated a need for additional research concerning simulator motion, and such research is still needed today. In fact, the question of whether or not motion cues influence transfer at all is as yet unanswered. Because of the possibility that erroneous motion cues might actually cause negative transfer, the issue of whether or not simulator motion is beneficial cannot be separated from a consideration of the fidelity of motion cues necessary to produce positive transfer and the relative transfer effectiveness and the cost-effectiveness tradeoff of increasing motion-cue fidelity. Studies are also needed to determine

the relationship between cockpit workload and the value of motion cues of varying experience levels.

Extracockpit visual cues. Because only selected visual cues are used by pilots, and visual cues are not required to perform every flying maneuver, the complete external visual environment does not need to be reproduced in a flight simulator. The real problem is determining exactly which visual cues are necessary.

An early study at the University of Illinois using a crude contact training device confirmed the value of visual cues for training private pilots (Flexman, Matheny, and Brown, 1950). Interestingly, the same device was ineffective for training military pilots (Ornstein, Nichols, and Flexman, 1954). The explanation given for this difference was that the value of extracockpit cues is limited by the quality of the instruction associated with their use.

Studies using slightly more complex extracockpit visual devices have confirmed their value (Creelman, 1955; Payne, Dougherty, Hasler, Skeen, Brown, and Williams, 1954). However, the value of extracockpit visual simulation in the learning of perceptual responses in flying in the absence of related psychomotor responses has not been substantiated (Creelman, 1955; Adams and Hufford, 1961).

A second group of studies has been concerned with training pilots to divide their attention between external visual cues and the instruments within the aircraft. Pfeiffer, Clark, and Danaher (1963) concluded that training does improve a pilot's time-sharing ability. Further, such training can be given in relatively inexpensive training devices (Gabriel, Burrows, and Abbott, 1965). The questions of whether or not the time-sharing skills learned in such devices transfer to flight and are retained over extended periods remain to be answered.

Smode, Hall, and Meyer (1966) point out that information on the value of contact devices is muddled because the utility of the visual device is so intertangled with the fidelity of the particular simulator being used. They indicate that more information is needed to clarify the value of contact displays both as a part of and independent of the specific simulator used. In addition, satisfactory methods of presenting visual and motion cues simultaneously need to be explored. For

example, is moving the visual display in response to the pilot's input equivalent perceptually to moving the trainer? A related issue is the value of open-loop training for closed-loop tasks. Again, the factor of level of pilot experience needs to be investigated. Finally, the effectiveness of inexpensive devices to teach time-sharing should be further explored, and the value of tachistoscopic training to increase instrument reading speeds needs to be determined.

Part-task versus whole-task training. Although a great deal of research has been concerned with part-task versus whole-task learning, the results of this research have limited applicability to pilot training. Traditionally, part-task training in verbal and simple motor tasks involves the development of component parts of a skill and subsequent practice on all parts concurrently. Part-task pilot training is typically molecular rather than atomic, often involving training on individual whole tasks that are later practiced in series with different tasks rather than in parallel with other parts of the same task. An example of a part-task flight trainer is a device that simulates with high fidelity only the attack phase of an air-to-air intercept mission (Nygaard and Roscoe, 1953).

The results of several studies specifically concerned with part-task trainers for pilots have supported the utility of such devices (Dougherty, Houston, and Nicklas, 1957; Miller, 1960; Parker and Downs, 1961; Pomarolli, 1965). A frequent limitation of part-task trainers is that they fail to provide an opportunity for practice in time-sharing attention among tasks (Adams, Hufford, and Dunlop, 1960; Hufford and Adams, 1961). A subsequent period of integration is necessary to allow students to perform various subtasks on a time-shared basis. On the positive side, part-task training seems to require less relearning after a period of rest (Hufford and Adams, 1961).

Smode, Hall, and Meyer (1966) suggest two areas for future research. First, the relative contributions of part-task and whole-task trainers need to be determined so that less expensive trainers can be used whenever appropriate. In addition, information concerning how task integration proceeds is needed. Eventually a pilot must scan his instruments, tune radio receivers, navigate, and

communicate, all while flying his airplane. Occasionally he may have to disarm a hijacker. Practice in doing all such things concurrently is required in a comprehensive training program.

Because almost any training must be part-task training to some degree, the real issue would appear to be the optimum size for each learning "chunk." Obviously, very few people get into a helicopter for the first time and solo; rather, training proceeds in steps. Optimum step size in pilot training is an open question.

#### Fidelity of Simulation

Muckler, Nygaard, O'Kelly, and Williams (1959) made a thorough review of early findings concerning the fidelity of simulation necessary for maximum transfer and found widely varying results. Several studies led to the conclusion that fidelity of simulation made little difference in the amount of transfer to the air. Mahler and Bennett (1950) found no differences in transfer among several training devices varying widely in fidelity. With the exception of performance on one maneuver, recovery from unusual attitudes, Wilcoxon, Davy, and Webster's (1954) results support Mahler and Bennett.

On the other hand, a study by Ornstein, Nichols, and Flexman (1954) isolated particular components of the pilot's task and found that training in a simulator of higher fidelity (Link P-1) consistently resulted in better transfer on each of 22 instrument maneuvers than training in either the Link AN-T-18 or C-8 trainers. Similarly, the results of Dougherty, Houston, and Nicklas (1957) favor trainers of higher fidelity. They found better transfer to the SNJ aircraft when pilots were trained either in an SNJ operational flight trainer or a procedural trainer than with a photographic mockup. However, in this study the advantage enjoyed initially by trainers of higher fidelity was negligible by the sixth air trial.

Each of the preceding four studies was conducted under similar experimental conditions, but the results are irreconcilable. Muckler, Nygaard, O'Kelly, and Williams (1959) concluded that studies concerned with fidelity of simulation are plagued by a variety of problems such as lack of generalizability from oversimplified laboratory tasks and inadequate measurement techniques. Before any definite

conclusions can be drawn about fidelity of simulation, more detailed information is needed to determine how such variables as instructor ability, variations in the difficulty of the training task, and pilot experience level affect transfer performance. As stated previously, there has been no experimental effort to determine the relationship between transfer of training and fidelity of simulated motion cues.

## ISSUES IN FLIGHT SIMULATOR EVALUATION

### What to Measure and How?

As noted by Blaiwes and Regan (1970) and more recently by Roscoe (in McGrath and Harris, 1971), three criteria must be considered in properly evaluating any training device: (1) efficiency of original learning, (2) transfer of what was learned in one situation to another, and (3) retention of what was once learned.

Original learning. To determine the effectiveness of synthetic flight trainers against any of these criteria, objective performance measures are necessary. One traditional measure of learning is instructor ratings. In general, such ratings tend to be subjective and as such are hampered by gross inconsistencies among independent observers. In an attempt to overcome many of the difficulties associated with subjective grading by check pilots, the development of objective flight inventories has been encouraged. One of the first of these was the Ohio State Flight Inventory which combined a series of five-point rating scales for each maneuver with some objectively scored items completed during flight. Ericksen (1952) summarized studies using this inventory.

In 1947 an extensive program to develop an objective checklist for pilot evaluation was begun under the sponsorship of the CAA through the National Research Council Committee on Aviation Psychology (Gordon, 1947; 1949). The decisions to include items were based upon critical incidents, accident reports, and job analyses. Tasks evaluated were arranged into a standard flight sequence, including both subjective and objective items. To maximize objectivity, graphics or pictures, quantitative data, and precise descriptions were used.

Another flight inventory, developed at the Human Resources Research Office, had as a goal the complete description of pilot performance (Smith, Flexman, and Houston, 1952). Based on reported critical behaviors in flying, the HUMRRO inventory consisted of two types of items: scale items (whether or not within predetermined tolerances) and categorical items (whether or not completed). Although its use has been limited to research, the inventory has provided reliable normative data to set standards for pilot training.

More recently, the Illinois Private Pilot Performance Scale has been developed (Povenmire, Alvares, and Jamos, 1970; Povenmire and Roscoe, 1973; Selzer, Hulin, Alvares, Swartzendruber, and Roscoe, 1972). This scale evaluates performance on each of ten maneuvers from the FAA's Private Pilot flight test guide. Four to six quantitative variables for each maneuver are scored by marking the maximum deviation from desired performance on appropriate scales. Equal weighting is given to all variables measured. Individual deviation scores are converted into standard scores based upon the observed variability among students tested for Private Pilot certification at the University of Illinois. Observer-observer reliability in excess of .80 has been found for this testing instrument (Selzer, Hulin, Alvares, Swartzendruber, and Roscoe, 1972).

Despite the increasing objectivity of pilot performance grading, the reliability of the so-called objective checks has been disappointing in routine use. According to Smode, Hall, and Meyer (1966), several factors contribute to the limited capability of objective measures. They are: check pilot biases, inadequate descriptions of acceptable performance, low validity based upon the failure to define precisely the critical skills to be assessed, and the need to give special training to check pilots on the use of objective measurements.

The shortcomings of check pilot ratings have given impetus to the development of automatic recording devices built into synthetic trainers. Danneskiold (1955) conducted a study to determine the feasibility of mechanical scoring devices. Although accuracy of measurement was an asset, the mechanical devices were limited by inflexibility, cumbersome size, and the failure to reflect



meaningful aspects of flight. Current research on automated performance measurement by Knoop (in McGrath and Harris, 1971) has thus far resulted only in tentative conclusions about requirements and feasibility. However, it is evident that semiautomatic performance assessment methods resulting from this research will receive considerable attention in connection with the evaluation of the effectiveness of new synthetic training devices.

The most elusive problem in the semiautomatic assessment of pilot performance is determining what ideal pilot behavior is. At present the real-world criterion most often used seems to be expert judgments of what maneuvers are essential and what range of performance variation can be tolerated. Another approach is the collection of normative data from the performance of experienced pilots. However, Flexman asserts that the variance among experienced pilots is greater than that among student pilots (in McGrath and Harris, 1971). Until some agreement is reached about what constitutes ideal pilot performance, evaluative techniques that measure deviations from a standard will be severely limited.

Transfer. A critical measure of the effectiveness of flight simulators is their transfer to performance in the air. Although early evaluations of flight trainers provided estimates of air time savings, many failed to include a control group, eliminating any objective measure of transfer of training (Conlon, 1939; Crannell, Greene, and Chamberlain, 1941; Greene, 1941).

A number of studies conducted at the University of Illinois were designed to measure the value of synthetic training in reducing the flight hours necessary to obtain a Private Pilot's license. Williams and Flexman (1949) measured the amount of flight time until students were judged ready to "solo." The results revealed no significant differences among groups of subjects having zero, two, or four hours of experience in a C-3 Link trainer. The experimenters recognized that the amount of flight time until ready to solo was not a good criterion for the evaluation of an early Link trainer, because skills required in landing and other presolo maneuvers requiring visual cues other than a horizon line were not easily taught in this type of trainer.

in their second study, evaluating the School Link, Williams and Flexman (1949) used three errorless trials on selected maneuvers as the criterion measure. The experimental group that received both Link training and inflight training learned the maneuvers to criterion with 28 percent fewer air trials and 22 percent fewer errors in flight than a control group receiving only inflight training. The experimenters suggested that approximately 25 percent of beginning flight training could be accomplished on the ground.

A further study by Flexman, Matheny, and Brown (1950) compared two groups of student pilots after ten hours of flight training. One group received no Link training and a second group received whatever Link training each individual student considered to be beneficial. Results indicated that the Link group was more proficient on a flight examination similar to the Private Pilot Performance Scale.

At about the same time that Link trainers were undergoing these evaluations, similar studies were conducted with the Link P-1 (SNJ) simulator which approximated a military aircraft, the T-6 (SNJ). In general, students receiving partial synthetic training performed as well or better than students trained solely in the air. Comparisons were based upon various criteria including number of flight failures and accidents, check flight grades, and total training hours (Flexman, Townsend, and Ornstein, 1954; Mahler and Bennett, 1950; Ornstein, Nichols, and Flexman, 1954; and Wilcoxon, Davy, and Webster, 1954).

The first and only studies that have allowed an assessment of transfer effectiveness of a specific flight simulator to its counterpart airplane on a maneuver-by-maneuver basis were conducted in 1950 by Flexman and reported 22 years later (Flexman, Roscoe, Williams, and Williges, 1972).

In 1969, almost 20 years later, Povenmire and Roscoe (1971) measured the transfer effectiveness of the relatively new Link GAT-1 and the Link AN-T-18 of World War II as used by typical flight instructors in a routine private pilot training program. Eleven hours of ground training in the GAT-1 saved an average of 11 hours (34.5 versus 45.5 for the control group) in the Piper Cherokee, thereby

yielding a Transfer Effectiveness Ratio of 1.00. An equal amount of training in the famous and venerable AN-T-18 saved an average of nine hours in the Cherokee for a Transfer Effectiveness Ratio of 0.82, thereby providing further justification for its continued widespread use more than 30 years after its invention.

Retention. Interestingly, the most common measure of training effectiveness, retention of material learned, has been generally ignored in the evaluation of simulators. Most studies fail to measure the permanence of simulator learning, despite the obvious importance of retaining flying skills. One notable exception is a study by Mengelkoch, Adams, and Gainer (1958) which measured simulator performance after a four-month retention interval. Unfortunately, both training and retention trials were conducted solely in a trainer with no measure of performance in the air.

Other studies in pilot training have not been designed to use the retention scores obtained as a measure of the effectiveness of various types and amounts of original learning including simulator training (Seltzer, 1970). Measurement of retention is hindered by such problems as variations in the original training of subjects, difficulty of controlling the amount of flying experience each individual pilot receives during the retention period, and unavailability of subjects after a sufficiently long retention period. The lack of simulator studies using a retention measure reflects the general insufficiency of information relating to retention of pilot skills or, for that matter, retention of any complex motor skill.

#### Cost Effectiveness

A trend in simulator development has been to duplicate as closely as possible every detail of the operational aircraft. As hardware technology develops, new capabilities are added to flight simulators resulting in a rapid cost spiral. Unfortunately, the training value of each added capability is seldom assessed. With inflated equipment costs, the need to weigh the relative value of physical fidelity against its cost has become evident.

In most of the quantitative transfer studies with simulators, the speed of learning by an experimental group, previously trained to a specified level of

proficiency in a simulator, has been compared with that of a control group receiving no simulator training. Transfer has been measured solely by the saving in flight time or reduction in errors with no regard for the amount of simulator training given members of the experimental group.

The study by Povenmire and Roscoe (1971), in which subjects were given a fixed amount of ground training, was an exception. It is doubtful that anyone would seriously propose replacing the GAT-1 with the AN-T-18 in a modern Private Pilot training program; nevertheless, a strong case could be made for doing so, as shown below in a cost effectiveness analysis based on the Povenmire and Roscoe data.

Assume the hourly cost of dual flight training to be \$22 (\$14 for the Cherokee plus \$8 for the instructor) and the corresponding values for the GAT-1 and the AN-T-18 to be \$16 (\$8 + \$8) and \$10 (\$2 + \$8), respectively. In a flight course normally requiring 46 hours in the air, if 11 hours of training in the GAT-1, costing \$176, save 11 hours in the Cherokee, costing \$242, each \$1.00 spent in the GAT-1 buys \$1.38 worth of air training. Similarly, if 11 hours of training in the AN-T-18 costing \$110, save 9 hours in the Cherokee, costing \$198, each \$1.00 spent in the AN-T-18 saves \$1.80 in the air.

#### Determining Essential Realism

Several approaches to lowering equipment costs are possible. The first requires a realistic appraisal of the amount of realism essential for the training task. Too often factors adding realism to a simulator are evaluated strictly in a go/no-go fashion. For example, the research question generally has been whether or not to include extracockpit visual displays, rather than what visual cues are necessary to achieve high transfer to flight.

Payne, Dougherty, Hasler, Skeen, Brown, and Williams (1954) used a relatively simple visual display, providing only a dynamic perspective outline of a runway on a screen in front of a 1-CA-2 (SNJ) simulator, to prepare a group of beginning students for solo flight in a T-6 aircraft. The transfer group reached

proficiency in landing with 61 percent fewer air trials and 74 percent fewer errors in landing approaches than did a control group trained only in the aircraft.

The inclusion of motion in present-day simulators is another example of the realism-versus-cost problem. Cohen (1970) estimated the cost of a three-degree-of-freedom motion system at about \$100,000 and a six-degree-of-freedom system at \$250,000. Such costs are not insignificant; nevertheless, most large-aircraft simulators have complex motion systems even though there is little evidence to indicate that such motion capability significantly improves ground-based training, and much of a pilot's training encourages him to disregard acceleration cues in flight.

Cohen (1970) indicated that a systematic research effort is needed to determine what kinds and what degrees of motion are essential for the flight training task. An initial effort in this regard might be to determine what aspects of motion a pilot can perceive and how acceleration thresholds vary under stress. Obviously, if certain types of motion cues cannot be perceived by the human operator, providing them is at best wasteful. In addition, if motion of some sort is included in a simulator, an effort should be made to avoid introducing misleading cues that hinder rather than facilitate transfer.

In view of the large sums invested in the design, development, and production of complex simulator motion systems, it is difficult to understand why there has been no objective, controlled experiment to assess their transfer effectiveness. An experiment by Matheny, Dougherty, and Willis (1963) showed that relatively faithful cockpit motion improves pilot performance in the simulator, presumably by providing alerting cues, and recent experiments at Ames Research Center (Guercio and Wall, 1972) and at the Aviation Research Laboratory of the University of Illinois (Roscoe, Denney, and Johnson, 1971; Jacobs, Williges, and Roscoe, 1972) support this finding. However, there is no evidence one way or the other to indicate that this improvement transfers to flight. The general experimental finding that relatively difficult training tasks yield higher transfer than easier ones suggests that transfer might be reduced as a consequence of adding motion cues that make the simulated flight task easier.

The evident reason that large sums are spent for simulator motion systems, with no evidence of their training value, is their high face validity. A high-fidelity motion system is a delight to any pilot; the illusion of flight is extremely realistic. The decision to include a complex motion system in a simulator is invariably determined by the enthusiasm of pilots, particularly ones in high places.

#### Training Objectives and Low-Cost Trainers

A related approach to lowering equipment costs involves identifying aspects of flight training that can be taught in low-cost devices. When a less complex training device is appropriate, it should not be overlooked in favor of complex simulators with higher face validity.

The failure to consider low-cost devices when procuring flight training equipment was well illustrated anecdotally by Prophet (1966). A procedures trainer that had cost over \$100,000 was pitted against a plywood, photographic instrument-panel mockup costing less than \$100. As predicted by Prophet, the static mockup fared as well as the costlier model for teaching cockpit procedures. Surprisingly, the mockup trainees also did as well as the simulator trainees on other tasks such as reading instruments and making precise control settings. Although the more expensive trainer had capabilities far beyond the scope of the mockup, training in the costlier device should be devoted primarily to task elements that cannot be taught effectively with less costly equipment.

The value of less than full simulation in a variety of flight training situations is obvious; cost reductions in training equipment may be quite large. However, the development and evaluation of simple training devices depend upon the imagination of the designer, the ingenuity of the instructor, and the financial support of the potential user.

#### INNOVATIONS IN SYNTHETIC FLIGHT TRAINING AND RESEARCH

Although the unresolved issues in synthetic flight training all have their origins in relative antiquity, progress toward resolution is evident. Terms such as

adaptive training, computer-assisted instruction, cross-adaptive measurement of residual attention, computer graphics, incremental transfer effectiveness, and response surface methodology have blossomed during the past decade. Progress in each of these areas shows positive acceleration.

### Adaptive Training

Although all personalized instruction is in a sense adaptive, the term adaptive training has come to refer specifically to the automatic adjustment of the difficulty, complexity, or newness of a training task as a function of the individual student's progress. Automatically increasing the average amplitude of the forcing function for a tracking task as a student learns, requiring a student to handle more and more subtasks simultaneously in accordance with his immediately preceding performance, and introducing new and different tasks as old tasks are mastered are all examples of adaptive training.

Adaptive training employs predetermined decision rules for the adjustment of a training system to the requirements of the individual trainee. Subsequent system outputs are determined by the previous output from the student. In effect, task difficulty is programmed to increase appropriately with increasing student proficiency.

The first formal application of automatically adaptive logic to the training of pilots has been incorporated into the Synthetic Flight Training System (SFTS) developed by the Naval Training Device Center for helicopter pilot training by the United States Army. In this system, one central digital computer drives four cockpit simulators in which four pilots learn to fly simultaneously under the supervision of a single instructor. The difficulty of certain flight tasks adapts automatically to the individual student's continuously measured performance.

The application of automatic adaptation of task difficulty to the SFTS (Caro, 1969) was inspired mainly by the studies of Hudson (1964) and Kelley (1966). In a conference on adaptive training held at the University of Illinois in 1970 (McGrath and Harris, 1971), it became evident that a central issue was the

nature of the adaptive logic employed. Specifically, should error limits be held constant as skill increases and the task becomes more difficult, as advocated by Kelley, or should error limits vary as the individual's performance improves, as advocated by Hudson? This issue is currently under investigation at the University of Illinois (Crooks, 1971).

#### Computer-Assisted Instruction

Automated adaptive skill training is a form of computer-managed instruction as is programmed cognitive training, which may or may not be adaptive. However, the term computer-assisted instruction (CAI) implies programmed cognitive learning in which an automatically branching logic allows each student to progress through a course at his own rate.

The application of CAI to the ground-school portion of the flight curriculum at the Institute of Aviation of the University of Illinois is currently in progress. Courses designed to prepare students for Private, Commercial, Instrument, Instructor, and Airline Transport Pilot certificates and ratings will be programmed for the PLATO system which eventually will have terminals throughout the nation. PLATO is the acronym for Programmed Logic for Automatic Teaching Operations.

The PLATO system (Bitzer and Johnson, 1971) was designed to aid both student and instructor in the educational process through use of the capabilities of the modern digital computer. The PLATO computer interacts with each student by presenting information and reacting to student responses. The actions of the computer follow the instructor's rules which specify what is to be done in each and every possible situation. A lesson constructed of such a set of rules can have a flexibility approaching that possible when each student has a human tutor. In fact, the rules defining a useful tutorial lesson presented by computer are quite similar to those implicitly used by a human teacher. For example, areas in which a student has proven competence are given minimal coverage, whereas areas in which the student lacks competence are developed more thoroughly.

In contrast to a conventional classroom in which a teacher manages 20 to 30 students simultaneously and can seldom give special attention to individual



students, PLATO appears to give each student undivided attention. This appearance results from the ability of the computer to identify and handle most student requests in a small fraction of a second. When several students request material simultaneously, the PLATO system processes their requests in turn. However, the last processed student seldom has to wait more than one-tenth of a second for a reply from the computer. To most students, one-tenth of a second appears to be instantaneous. One aspect of individual attention is rapid feedback. The student receives immediate knowledge of the correctness of his responses.

The primary application of PLATO to the training, certification, and currency assurance of pilots will be in the cognitive domain, although PLATO is also capable of certain types of perceptual-motor training. The individual attention capability of PLATO together with computational and graphic display abilities allow authors of ground school courses to select and present stored material, such as special characters, photographic slides, and either printed or audio messages, and to construct geometric figures or graphs activated by instructions of either the author or the student. A constructed graphic display, for example, might be used to allow a student in an aviation course to specify the shape and construction of an airfoil. PLATO could then produce a cross-sectional view of the airfoil on the student's plasma display screen. Upon request, PLATO might also show the paths of air molecules flowing around the airfoil in flight.

As the number of terminals grows throughout the country, it will become increasingly possible and desirable to leave much of the certification and currency assurance testing to the PLATO system. Doing this would allow students to take FAA tests at their own convenience and would also free many FAA examiners for more important tasks. When legislation is passed requiring all pilots to undergo periodic recertification, the extra load on the present testing system is going to be enormous. Using CAI techniques to conduct these tests will provide great relief to the system.

### Cross-Adaptive Measurement of Residual Attention

The automatically adaptive measurement of a pilot's "residual attention" while performing routine flight tasks can consist of anything from rhythmic tapping on a microswitch with a finger or foot (Michon, 1966) to complex information processing (Ekstrom, 1962; Knowles, 1963). Such tasks serve at least two functions. They provide an inferential measure of the pilot's mastery of the primary task, and they can create realistically elevated workload pressures typical of those encountered in flight emergencies. The demands imposed by such tasks can be made to cross-adapt automatically to the pilot's performance of his primary flight control task. The better he flies, the faster flows the information to be processed. In this way the pilot's total cockpit workload capacity can be measured as a function of his level of training or the decay in his proficiency following periods of inactivity.

The use of automatically adaptive and cross-adaptive secondary tasks for the measurement of residual attention has been applied both in the experimental study of flight display and control design variables (Kraus and Roscoe, 1972) and in the prediction of success in pilot training (Damos, 1972). From these experiments, it has become evident that the technique also can produce a powerful instructional effect in the important areas of attention sharing and decision making. Furthermore, it is well established that pilots show small decrements in flying skills over long periods of inactivity but show large decrements quickly in procedural efficiency, particularly in situations requiring attention sharing and rapid decision making.

Thus, residual attention tasks provide not only a measure of the initial attainment of proficiency but also a quick and reliable means of testing the currency of certificated pilots. Tasks similar to those already employed effectively in human engineering experiments can be integrated into either ground-based or airborne flight trainers, but new techniques will have to be developed for their routine use in pilot training, certification, and currency assurance.

### Computer Graphics

The simulation of extracockpit visual cues is essential for training in ground-referenced maneuvers involving great danger in actual flight. Extremely costly visual systems have been employed for training in high-speed, low-altitude military operations and in emergency procedures, such as single-engine approaches and engine loss on takeoff in multiengine transport aircraft. High costs are justified in such cases. However, there is an urgent need for less costly but nonetheless effective visual systems for use in various phases of flight training. Perhaps the greatest payoff would be found in the initial training of pilots to land an airplane safely with a minimum of exposure to the hazards of presolo and early post-solo landing practice.

Valverde (1968) emphasizes the importance of understanding the capabilities and limitations of visual equipment in order to evaluate properly its use to meet specific training requirements. He points out, for example, that a large generator is necessitated by the use of a large visual envelope. Therefore, if a small envelope can be used, the cost saving will be extended to other equipment dependent on it.

A computer-generated line-drawing display system (LDS-1) developed by the Evans and Sutherland Computer Corporation (Ogden, 1970) fits into Valverde's small envelope category. This graphic display system allows automatic windowing and perspective projection of three-dimensional objects, such as an aircraft carrier or an airport with runways and hangars, and therefore lends itself to the simulation of approaches to landings and other contact flight operations requiring a limited field of view.

The Advanced Simulator for Undergraduate Pilot Training (ASUPT) being developed for the Flying Training Division of the USAF Human Resources Laboratory presents an enormous computer-generated visual envelope around the simulated cockpit of a T-37 airplane (Gum, Knoop, Basinger, Guterman, and Foley, 1972; Smith, 1972). This application of computer graphics presents a somewhat less than literal black and white image of the outside world on seven 36-inch circular CRTs,

each framed by a pentagonal display window, in a faceted arrangement covering the full forward, lateral, and vertical limits of the external visual field from the cockpit of the T-37. This colossal device is designed to allow the systematic experimental determination of the external visual cues contributing significantly to contact flight training.

Another advanced application of computer graphic techniques, developed jointly by Hughes Aircraft Company and the University of Illinois for the Federal Aviation Administration, generates a moving-map display for cockpit presentation, continuously showing present position, heading, and area navigation guidance commands. Similar systems have been developed by several companies including Boeing, Astronautics, and Sperry-Phoenix.

#### Incremental Transfer Effectiveness

To determine the relative value of simulator training, Roscoe (1971; 1972) proposed the concept of "Incremental Transfer Effectiveness" which postulates a function found by comparing successive increments of time spent in one training task with successive increments of time saved in subsequent training. When the Incremental Transfer Effectiveness Ratio drops below the ratio of the hourly cost for ground trainers to that of training aircraft, continued ground training is not cost effective.

The Incremental Transfer Effectiveness concept recognizes the decreasing value of successive increments of simulator training in terms of the time saved in generally more expensive equipment. Povenmire and Roscoe (1973) demonstrated the negatively decelerated relationship between hours saved in the Cherokee airplane and hours spent in the Link GAT-1 in the training of a Private Pilot. Comparison of the Incremental Transfer Effectiveness Functions of different training provides a rational basis for procurement and use in economic terms.

#### Response Surface Methodology

Previous research has concentrated on the separate effects of numerous variables important in simulator training, but little effort has been directed toward

investigating the simultaneous effects of these variables. It is possible that important interactions may be present or that the effect of one variable may be so strong that it overrides other variables. Methodologically, however, it is extremely difficult to examine many variables at once without quickly approaching an unwieldy number of essential data points. For example, if three variables were observed at three levels in a traditional factorial analysis of variance design, 27 treatment combinations or data points would be required for each replication of the design. If seven variables were investigated at three levels each, 2187 data points would be required for each replication. Obviously, the latter experiment would not be conducted. It is also not surprising that such a methodological impasse was quickly realized in early research on flight simulators (Williams and Adelson, 1954).

Research techniques called Response Surface Methodology (RSM) have been developed for investigating many variables simultaneously. Box and Wilson (1951) originally used RSM to determine the optimum combination of variables for producing the maximum yield of a chemical reaction. The RSM designs minimize the number of data collection points necessary to determine a multiple regression prediction equation describing the relationship between a predicted score and the experimental variables. Details and examples of this technique are provided by Box and Hunter (1957) and Cochran and Cox (1957).

Recently, Williges and Simon (1971) discussed the utility of using RSM techniques in human performance research. In addition to the economy of the data collection, the designs are flexible and efficient. The designs are flexible in that the data can be collected in sequential order. At the end of each stage of data collection, the experimenter can analyze his results and decide on the appropriate data points to investigate during the next stage of experimentation. The designs are also efficient in that controls are readily available for undesirable fluctuations when the experiment is extended over time. However, certain design modifications are necessary before these techniques can be used successfully to assess human behavior. Some of these considerations are described by Clark and Williges (1972).

With the increased use of RSM in engineering research, it is surprising that limited applications have been made to behavioral research. Only two studies concerned with problems of human learning have used RSM. Meyer (1963) used RSM to study the effects of degree of original learning, time between interpolated and original learning, length of the interpolated list, and degree of interpolated learning on the amount of retroactive inhibition in verbal learning. He plotted a response surface relating the four independent variables to amount of recall. Williges and Baron (1972) used RSM to plot a transfer surface of trials to criterion in an epicycloid pursuit rotor task as a function of tracking speed during training, time between training trials, and number of training trials on a simple pursuit rotor task.

The RSM technique appears to be a viable procedure or model for systematically developing a training simulator. First, it allows for simultaneous investigation of many variables. Second, the sequential research strategy of RSM provides an orderly procedure for determining the variables of importance in simulation to maximize learning, transfer, and retention. Third, the resulting prediction equations can be used to determine tradeoffs among the various independent variables important in simulation to maintain a specific level of learning, transfer, and retention. Finally, the separate RSM prediction equations for level of learning, transfer, and retention can be compared to determine the necessary tradeoffs among the important simulation variables to optimize systematically the combined level of learning, transfer, and retention provided by a particular simulator.

One overall limitation of research on training simulators appears to be that simple piecemeal approaches are used to solve complex research problems. The potential power of RSM is that it allows the investigator to examine the problems of simulation research from a complex, multiparameter, yet systematic, point of view.

## PROSPECTUS

User demand for air transportation, recreational flying, and an ever-increasing variety of agricultural, industrial, and scientific flight operations is placing unprecedented pressures on the National Airspace System (NAS). The rapidly increasing complexity of the system itself is demanding new levels of flying skill and knowledge to which few pilots have been trained, and training costs to prepare pilots to operate safely and effectively in the NAS are becoming prohibitive. Furthermore, there is inadequate assurance that those presently flying are qualified to do so, and this problem is growing.

What is needed is a scientifically rigorous investigation into fundamental flight requirements, including not only the perceptual, cognitive, and motor skills required of pilots, but also the attitudes and judgmental factors essential to safe flight. The investigation must start with the identification of the types of flight operations, or missions, that will be undertaken during the foreseeable future and the functions to be performed by pilots in such operations. From this functional analysis must be derived the minimum standards of skill, knowledge, and judgment required of all categories of pilots permitted to fly in the National Airspace System. Current pilot training and certification practices must be evaluated in this new context. Where existing requirements and methods are found to be deficient, new approaches must be devised to close the training and certification gaps at a bearable cost.

A new pilot training, certification, and currency assurance system is needed, one that will automatically qualify each pilot for his particular level of operation at a bearable cost to him as well as to the aviation community. Representative advances in training technology applicable to this objective include computer-aided cognitive training and testing, automatically adaptive skill training and performance assessment, and the extended use of simulation to previously unexploited areas of pilot training, certification, and currency assurance.

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